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FINAL TECHNICAL REPORT

on

Chromospheric Activity in Algol Binaries

Principal Investigator: **Mercedes T. Richards**

Institution: University of Virginia, Charlottesville, VA 22903

Grant Number: AFOSR F49620-92-J-0024

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Abstract

Algol-type binary star systems contain a cool Sun-like star and a hotter blue star. The cool star has a magnetic field many times more powerful than that of our Sun, with starspots that are similar to sunspots. The magnetic fields of Algol binaries are powered by the rapid rotation of the cool star. In the short-period Algols, the cool star rotates once every 6 days or less while our Sun rotates much more slowly once every 28 days. This difference in rotation rates can account partially for the differences which we see in the magnetic structures like the chromosphere and corona. These short-period Algols contain a stream of gas which is stripped off the cool star by the gravitational pull of the hotter blue star, strikes the hot star, then circles it to form an asymmetric ring of gas. Mercedes Richards was the first astronomer to discover starspots on the cool star in an Algol binary. More importantly, she has been trying to understand how the extensive magnetic field of a star like our Sun would affect the flow of gas between the two stars, and especially the blue star. She was also the first astronomer to produce a reconstructed Doppler (velocity) image of gas streams in the class of interacting binaries, and also first to image the chromospheres and accretion disks in Algol binaries. This information will help us to understand how Sun-like stars influence the evolution of a binary system.

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1. OBJECTIVES

The P.I.'s main objective was to examine the connection between the chromospheric activity of cool stars like the Sun and those which are found in the Algol-type binaries. These binaries contain an F – K giant or subgiant secondary (the fainter, less massive star) and a B5 – A5 V primary (the more luminous, more massive component). The cool F- to K-type secondaries in short-period Algol-type binaries are expected to be magnetically-active (i.e., demonstrate chromospheric and coronal activity) because of their rapid rotation and outer convective layers. However, magnetic activity is not usually associated with these binaries because the secondaries are faint relative to the luminous primaries at visible wavelengths. Nevertheless, the detections of both stellar flares and starspots in these binaries have provided evidence of magnetic activity associated with the secondary star. These Algol secondaries are similar to the doubly-active RS Canum Venaticorum (RS CVn) binaries which have K-type primaries with F- to G-type secondaries and display magnetic properties which include weak CaII H and K emission; brightness variations in the light curve of $\lesssim 0.1$ mag. indicative of the motions of starspots; coronal X-ray emission; weak radio flares; nonthermal gyrosynchrotron radio emission; ultraviolet and infrared excesses; and alternate increases and decreases in the orbital period of the binary.

Recent work on Algol (β Persei), the prototype of the Algols, outlined evidence of starspot activity in the infrared light curves, and both Exosat and Ginga observed X-ray flares from this system. These flares also emit radiation at Hα, and should influence the observed Hα line profiles from Algol. Therefore, the P.I. proposed to determine the contribution of flares to the observed Hα line profile for a selected group of Algol-type binaries. In particular, the P.I. was to determine the strength of the flare at Hα and compare it with the Hα emission and absorption from other more standard forms of circumstellar material like gas streams and accretion disks which are associated with the primary star. The P.I. proposed also to obtain new infrared light curves of Algol binaries to study starspot activity.

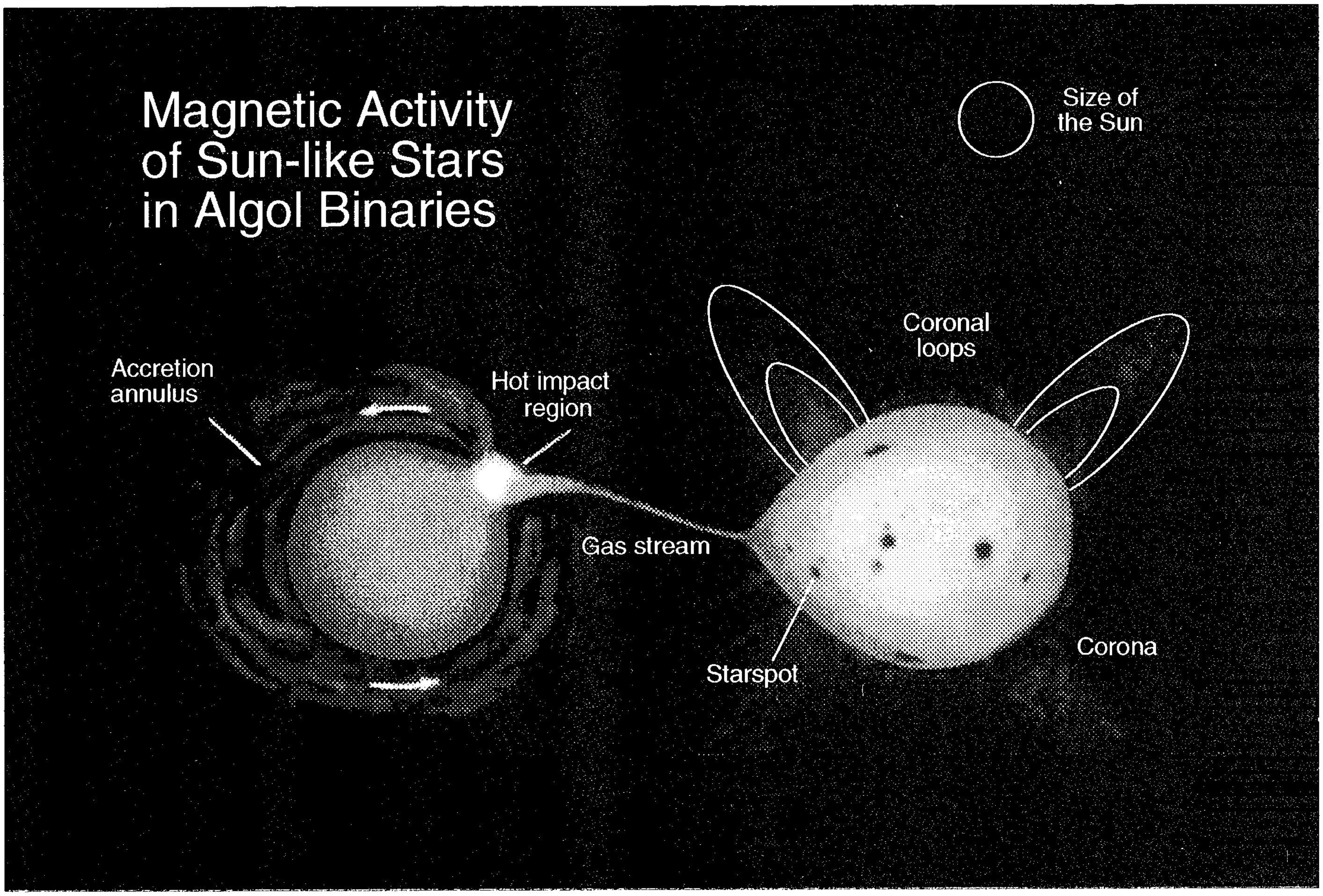

Figure 1: Schematic representation of an Algol-type interacting binary derived from a model illustrated in Richards (1992, *Astrophys. J.*, 387,329). The stars are so close that the magnetically active giant or subgiant star (the orange pear-shaped star) is actively transferring gas to its hotter, more luminous companion (the blue star). The original color version of this model was published in *Sky & Telescope* (1992), 84, 132.

2. SUMMARY OF EFFORT

Over the past four years, the P.I. and her students have used several approaches to study magnetic activity on the rapidly-rotating cool components in short-period Algol-type binaries which have orbital periods (P_{orb}) less than 6 days. She initiated and has continued her observing campaign to collect infrared photometric light curves of Algol binaries to study starspot activity. This work is now being done with the collaboration of astronomers at Teide Observatory in the Canary Islands, Spain. Since 1990, she has also led a determined campaign to observe short-period Algols at positions around the entire orbit. She has continued the monitoring and analysis of Hα spectra of short-period Algols with the help of her Ph.D. student, and they have now over 2200 Hα spectra of 18 Algols collected at two national observatories: the National Solar Observatory (NSO) and Kitt Peak National Observatory (KPNO). In addition, the P.I. has organized several simultaneous multiwavelength (ultraviolet, visible, infrared, radio) and multi-site (USA, Europe) observing campaigns to understand better how the magnetic field influences the mass transfer process.

The Hα spectra were used with the technique of Doppler tomography to produce two-dimensional velocity images of the emission sources in Algol binaries. Several sources of Hα emission have now been found including images of chromospheres, gas streams and accretion disks. In fact, these results have provided the first images of chromospheres and accretion disks in the entire class of Algols, and the first convincing images of gas streams along the predicted gravitational path from the mass loser to the mass gainer in the Algols and in *the entire class of interacting binaries.* The P.I. has also used numerical hydrodynamical simulations to try to separate the contributions of the mass transfer process from that of the magnetic field of the mass losing star. This work has helped in the overall interpretation of the observations.

3. ACCOMPLISHMENTS

Algol-type binary star systems contain a cool Sun-like star and a hotter blue star. The cool star has a magnetic field many times more powerful than that of our Sun, with starspots that are similar to sunspots. The magnetic fields of Algol binaries are powered by the rapid rotation of the cool star. In the short-period Algols, the cool star rotates once every 5 days or less while our Sun rotates much more slowly once every 28 days. This difference in rotation rates can account for the differences which we see in the magnetic structures like the chromosphere and corona. These short-period Algols contain a stream of gas which is stripped off the cool star by the gravitational pull of the hotter blue star, strikes the hot star, then circles it to form an asymmetric ring of gas. The P.I. has been trying to understand how the extensive magnetic field of a star like our Sun would affect the flow of gas between the two stars, and especially the blue star.

When this research was initiated four years ago, there was little hope of spectral evidence of magnetic activity in Algol binaries. However, the P.I. now has a database of Hα spectra of short-period Algols which does not exist anywhere else in the astronomical community. With these spectra, the P.I has been able to reconstruct velocity images (called Doppler tomograms) of Algol binaries even though these systems cannot be resolved with a telescope. The images have provided evidence of chromospheric Hα emission and definitive proof of the existence of gas streams, as well as evidence in extremely magnetically-active systems that the magnetic field can alter the normal gravitational free-fall path of the gas stream and influence the overall distribution of gas flows in the binary. Over time, these processes will influence the evolution of the binary. The P.I. is the first astronomer to produce a Doppler image of gas streams in the class of interacting binaries, and also first to image the chromospheres and accretion disks in Algol binaries. This information will help us to understand how Sun-like stars influence the evolution of a binary system.

The details of specific accomplishments are given below. The references quoted are listed in the Bibliography (Section 4), Peer Reviewed Publications (Section 6), and Conference Presentations (Section 7a).

(a) Survey of Evidence of Magnetic Activity

The P.I. compiled observational evidence of magnetic activity in 15 Algol binaries and found that there is a paucity of information on the cool stars in these binaries (Richards 1992; Richards & Albright 1993). The systems chosen had orbital periods typically less than 6 days since short-period rapid rotators are more likely to display magnetic activity than their long-period counterparts. The properties examined included changes in the orbital period of the binary, possible detections of Ca II H and K emission and hydrogen Balmer line emission, the x-ray luminosity determined from x-ray flares, detections of radio emission, and evidence of variations in the brightness of the cool secondary which are linked to motions of starspots on the cool secondary star (starspot activity). The survey showed that although six of the chosen binaries displayed evidence of variations in the brightness of the secondary, β Persei is the only Algol binary for which there was strong evidence of starspot activity. In this case, the evidence was found by the P.I. (Richards 1990) from a study of the only complete 1.2 μm light curves of that system that were obtained from 1960 to 1963.

The P.I.'s work on magnetic activity in the Algols was described in a new book titled *The Realm of Interacting Binary Stars,* 1993, edited by J. Sahade, G. E. McCluskey, & Y. Kondo (Dordrecht: Kluwer). The need for new infrared photometry of the Algols was emphasized in this book, as has been done by the P.I. for several years. The limiting factors are the large amounts of observing time required on an infrared photometer or spectrograph (Richards & Albright 1993). Moreover, any evidence of magnetic activity would appear as weak features in the light curve or spectrum.

(b) Data Collection

The spectroscopic observations of Algol binaries discussed in this work were obtained with the spectrograph and CCD on the 0.9m Coudé Feed telescope at Kitt Peak National Observatory (KPNO) and the 1.5m telescope at McMath-Pierce Solar Observatory (NSO) from 1990 October to 1994 December. These observations were originally obtained for the study of mass transfer, supported by a research grant from the National Science Foundation. However, the later observations were obtained jointly for the study of magnetic activity as it influences the mass transfer process. The P.I.'s Ph.D. student Mr. G. Albright obtained most of the observations as part of his thesis (see Richards & Albright 1994a).

The 1990 and 1991 NSO data were 32 Å wide with a reciprocal dispersion of 2.7 Å mm^{-1}, while the 1992 observations have a spectral field of 73 Å and a reciprocal dispersion of 6.09 Å mm^{-1}. The KPNO data have a spectral field of 177 Å and a dispersion of 14.8 Å mm^{-1} (1992 spectra), or a spectral field of 345 Å and a dispersion of 7.0 Å mm^{-1} (1993 spectra). The Coudé Feed was used very effectively by Albright to cover the orbits of up to 9 binaries during a single 7-night observing run and reduce any long-term variability in the data. As a result, the P.I. and Albright now have a unique data set which contains nearly complete orbital coverage of several binaries within 3 orbital cycles. Some systems were observed in subsequent years to provide a secular perspective. These data are mostly Hα spectra, but observations of the Hβ and CaII H and K lines were also collected for selected binaries. The data obtained since 1990 October include Hα spectra of over 14 Algols, with limited coverage of 4 others: V505 Sgr, RZ Cas, TW Cas, TV Cas, δ Lib, RW Tau, TW Dra, β Per, TX UMa, U Sge, S Equ, U CrB, RS Vul, SW Cyg, TT Hya, AU Mon, and RY Gem. In addition, Hα spectra of the RS CVn binary, V711 Tau (or HR1099) were obtained for comparison with the spectra of the Algols. The spectra of V711 Tau were expected to display evidence of chromospheric activity only, with no accompanying evidence of mass transfer, while the spectra of the Algol binaries were expected to show evidence of both mass transfer and chromospheric activity.

In the short-period Algols, the luminosity of the stars is much greater than that of the emission sources, namely the circumstellar gas and the chromosphere of the cool star. As a consequence, it is difficult to study the gas flows unless the photospheric component is removed. To achieve this end, the combined theoretical (ATLAS9) LTE stellar photospheric Hα line profile (Kurucz 1991) was subtracted from the observed line profile to produce "difference profiles" at each orbital phase, with line strengths scaled to the total continuum flux of each system. The details of this procedure are described by Richards (1992, 1993). These difference profiles represent the contributions of all *non-photospheric* gas flows in the binary, namely those produced by Roche lobe overflow and the chromosphere of the magnetically active cool secondary star. The difference profiles typically show blends of emission and absorption, with either single or double-peaked emission at out-of-eclipse phases. Broad absorption profiles are seen during primary eclipse, and often a narrow emission feature is superposed on the absorption near the middle of this eclipse.

(c) Spectroscopic Evidence of Activity

Spectroscopic evidence of magnetic activity uncontaminated by other processes (e.g., mass transfer) was very difficult to find. In the RS CVn binaries, whose stellar components have comparable brightnesses, the usual magnetic indicators are the Hα and Ca II H and K lines. In these binaries, there is no mass transfer by Roche lobe overflow as in the Algols, so all of the Hα emission is linked to chromospheric activity. However, in Algol binaries, the Hα emission and absorption have been traditionally associated with the mass transfer process, and not to chromospheric activity. Undergraduates Ms. L. Bowles and Ms. M. Lugo assisted the P.I. in 1993 in a study of the shape of the Hα line profile due to chromospheric activity and mass transfer, but they were unable to separate the two effects. An initial study by the P.I. (Richards & Albright 1993) showed that the relative contribution of chromospheric activity to the Hα line was expected to be small ($\sim$10%), but the structure of the magnetic field of the secondary might still influence the gas flows in the binary. In a later study of reconstructed Hα emission sources (Richards, Jones & Swain 1996), the P.I. showed that in one system, β Per, the chromospheric emission could be as much as one half of the emission from the gas stream, and comparable to other emission accretion sources (see Section 3(d) below), so that the relative contribution of chromospheric emission to the total Hα emission was approximately 15%. This is in fairly good agreement with the earlier estimate.

With all the Hα spectra in hand, the P.I. did not find any convincing evidence of flares at Hα. Moreover, spectra of the Ca II H and K lines (3968Å, 3934Å) of β Per and RZ Cas were obtained in March 1993 at the NSO, and of U Sge in June 1994 at KPNO. These spectra showed no evidence of emission indicative of magnetic activity. These Ca II lines are very sensitive to magnetic activity and are absent or weak in the spectrum of the non-magnetically active hotter primary companion in Algol binaries. Since the relative contribution of the cool secondary is at its highest in the infrared part of the spectrum, then there should be evidence of emission or excess absorption in the Ca II lines at these wavelengths. So in July, 1993, Dr. B. W. Bopp (University of Toledo) assisted in a pilot campaign to examine the Ca II infrared triplet (8500 – 8700 Å). Dr. K. Strassmeier (University of Vienna, Austria) also made similar attempts in 1994 to detect the triplet in the spectra of δ Lib, but without success.

(d) Doppler Tomography

The most satisfying evidence of magnetic activity in the optical spectra of Algol binaries has come from a more intense study of the Hα spectra. The P.I. used the more than 2200 Hα spectra of short-period Algols collected around the entire orbit of each binary to locate the contributions to the hydrogen line from the chromosphere and the usual products of mass transfer. This was done with the aid of an image reconstruction technique called *Computerized tomography* (Herman 1980) which is routinely used in medicine to reconstruct three-dimensional images of parts of the human body from two-dimensional CAT scans or X-ray images. In the case of binary stars, the spectra can be mapped into a two-dimenaional tomogram by using the radial velocities of the spectra lines as one dimension and the orbital phases around the binary as the second dimension. This technique of *Doppler tomography* produces images of the sources of hydrogen in the orbital plane of each binary system, not in the usual spatial dimensions but in dimensions of velocity (Marsh & Horne 1988; Robinson, Marsh & Smak 1994). Doppler tomography was first applied by Marsh et al. (1990) to the Hβ, He I (λ4471) and He II (λ4686) spectral lines of the cataclysmic variable U Gem. An atlas of Doppler tomograms of 18 cataclysmic variables was also produced by Kaitchuck et al. (1994). Some of these images display a toroid of emission (an accretion disk) centered on the white dwarf mass gainer. In the case of Algol-type binaries, the P.I. used the technique of Doppler tomography to analyze the Hα difference profiles of RW Tau, β Per, TX UMa, U Sge, U CrB, S Equ, RS Vul, SW Cyg, and TT Hya , as well as V711 Tau (the RS CVn binary). The results have been reported in (Jones & Richards 1992; Richards, Albright, & Bowles 1994, 1995a,b; Richards, Jones & Swain 1996; Richards & Albright 1995; Albright & Richards 1996). The P.I. was assisted by undergraduate students Mr. R. Jones and Ms. L. Bowles, as well as graduate student Ms. M. Swain.

In the first study, the P.I. used photographic Hα spectra of β Per, which were collected in 1976 and 1977 to generate a Doppler tomogram. Jones and the P.I. found that the source of the Hα emission in β Per, was concentrated near the inner Lagrangian point (L_1) between the two stars (Jones & Richards 1992). However, if the data were separated into specific bins designed to occult or include the gas stream, then the Doppler images showed several sources of the Hα emission (Richards, Jones & Swain 1996). The strongest source is found along the gas stream between the two stars, and is due to the mass transfer process. It is prominent in the data set over orbital phases, $\phi = 0.60 - 0.30$. The weaker emission sources were revealed in the data from $\phi = 0.30 - 0.60$. These latter sources include an accretion annulus around the

mass gaining star, and a region over the secondary star which the P.I. associated with the chromosphere.

Subsequent studies involved the use of the spectra described in Section 3(b) of this report. The P.I. found several sources of Hα emission, including evidence of chromospheres, in the 1993 and 1994 observations of β Per, U Sge, U CrB, RS Vul, SW Cyg, S Equ, and TX UMa. A preliminary morphological study of the Doppler tomograms suggests that there are as many as 7 sources of emission. The tomograms of RS Vul (1993), U Sge (1994), U CrB (1994) and β Per (1976/1977) all show distinct elongated emission along the gravitational free fall path of the gas stream trajectory from the L_1 point towards the primary star (Richards, Albright & Bowles 1994, 1995a,b). The collimation of the gas stream was more pronounced in U CrB (1994) than in the other systems. Difference profiles of some systems, e.g., U CrB (1993) and U Sge (1993), show near-Keplerian accretion disks around the mass gaining star in addition to the gas stream (Albright & Richards 1996). So it is apparent that the Algols with $P_{orb} < 4.6$ days periodically change from a state where the gas stream is strong to one in which the accretion disk is strong, but both components are always present. For the binaries with $P_{orb} > 4.6$ days, e.g., SW Cyg (1994), the tomogram displays a prominent, almost Keplerian disk which is similar to those found in the cataclysmic variables (cf. Kaitchuck et al. 1994).

Another emission source has the same velocity as the secondary star, hence may arise from the chromosphere of that magnetically active star. This source was prominent in RS Vul (1993), TX UMa (1992, 1993, 1994), β Per (1992, 1994), and RW Tau (1994). The strongest emission source in RS Vul is centered on the velocity of the cool G1 III star, while in the remaining Algol systems the chromospheric source is weaker relative to other emission sources. The tomogram of RW Tau (1994) is similar to those of β Per. A Doppler tomogram of the Hα emission in the RS CVn binary V711 Tau was also made. The orbital coverage of this binary was not as good as we would have liked, but this system provided a useful check on the back-projection procedure. As expected, the tomogram of V711 Tau displays no evidence of mass transfer via Roche lobe overflow, but contains a strong source centered on the more active K1 IV component, with a less intense source extending to the less active, fainter G5 IV companion. There is no obvious double chromospheric source in this case because of the relative strengths of the K to G chromospheres. While RS Vul contains a strong gas stream source, the similarities between this Algol binary and V711 Tau are quite interesting.

The relative contribution of the chromospheric emission source compared to the total emission sources is different from system to system (Richards & Albright 1995). When compared with the Hα emission from V711 Tau, the chromospheres of the Algol-type binaries β Per, U Sge, U CrB, RS Vul, SW Cyg, S Equ, and TX UMa are 0.2 to 6.2 times as powerful since they contribute $\sim 4\% - 30\%$ of the continuum flux at this wavelength. The chromospheric source in RS Vul is the strongest of all the systems studied, and is 6 times stronger than that in V711 Tau. Moreover, the tomogram of TX UMa (1992) suggests that the gas stream does not follow the gravitational trajectory. One explanation is that the magnetic field associated with the secondary in this system is strong enough to dominate the gravitational process. Supporting evidence for this explanation has come from both radio and x-ray observations of TX UMa (Richards & Albright 1995).

In summary, these tomographic studies have now provided the first convincing images of gas streams along the predicted gravitational path from the mass loser to the mass gainer in the Algols and in the entire class of interacting binaries. Moreover, they have produced the first images of chromospheres in the entire class of Algols, and found that the chromospheric emission is comparable to that from other individual emission sources in each binary. The chromospheric emission from the Algols is comparable also to that from the RS CVn binary, V711 Tau.

(e) Multiwavelength Studies

In June 1994, the P.I. and Albright coordinated an international multiwavelength campaign to obtain simultaneous Hα and ultraviolet spectra and 8.4 GHz radio continuum observations to discern the relative contributions of chromospheric emission associated with the magnetically-active secondary and the products of Roche-lobe overflow on the observed Hα line profile. The IUE spectra should arise primarily from the mass transfer process, but the Hα spectra could also arise from the chromosphere of the secondary; while the detection of a radio flare might signal increased chromospheric activity. The campaign involved 5 observatories in 3 countries (U.S.A., Spain, Czech Republic), at three wavelengths.

In 1994 December, another simultaneous Hα and radio continuum flare search was organized to study β Per (an Algol binary) and V711 Tau (HR 1099: an RS CVn binary). From 1994 December 1 – 7, Hα spectra were obtained by the P.I. and Albright from KPNO and by Dr. P. Koubský (Astronomical Institute, Academy

of Sciences, Czech Republic) with the 2m telescope at Ondřejov Observatory, while an 8.4 GHz radio flare search was done with the 140 foot telescope at Green Bank Radio Observatory with the assistance of graduate student E. Murphy, and Dr. R. Rood (University of Virginia) from December 5 – 8, 1994. No flares were reported during either simultaneous campaign, but the null-result may serve to illustrate the appearance of the Hα spectra during quiescient flare states.

(f) Continuous Radio Flare Survey

A continuous long-term radio survey of β Per and V711 Tau has been in effect since 1995 January to study the flaring timescales of these systems at 2 GHz and 8 GHz (Richards, Waltman, Foster & Ghigo 1995). The observations are being collected with the Naval Research Labs (NRL) interferometer at Green Bank Radio Observatory (USA). The campaign has been successful in detecting at least four strong flares with continuum flux of $\sim$ 0.5 Jy at 8 GHz in β Per and four strong multiple flares with strength up to $\sim$ 0.8 Jy at 8 GHz in V711 Tau. The time scale of these flares is 1 – 2 months. These flaring timescales may provide a clue to the processes which result in the extreme variability of the Hα emission in systems like U CrB and U Sge, or those which influence the gas stream trajectory in TX UMa.

(g) Infrared Photometry

The infrared photometric observing campaign to study starspot activity was initiated by the P.I. in 1994 after a series of setbacks. The program involved the collection of J, H, and K photometric light curves of Algol binaries which would be used to determine the sizes and distribution of spots on the magnetically active star (cf. Richards 1990). In 1992, the P.I. applied for time to use the infrared photometers on the 1.3m telescope at KPNO in Tucson (Arizona, USA) and the 1.5m Carlos Sanchez Telescope at Teide Observatory in Tenerife (Canary Islands, Spain). She had hoped to start observing in Spring 1993 but the KPNO telescope was oversubscribed for the Spring session, and the Otto detector used with the infrared photometer was later permanently discontinued. The Carlos Sanchez Telescope also was shut down for unplanned maintenance until Fall 1993. In an attempt to overcome these problems, the P.I. and her students identified the public and private observatories which have infrared photometers (Richards & Albright 1994b). However, the P.I. was able finally to initiate her program in February 1994.

Partial JHK light curves of β Per, RW Tau, and TX UMa were obtained from February 17 – 27, 1994. The project is continuing with the assistance of Dr. M. Jesus Arevalo and Dr. C. Lazaro of the Astrophysical Institute of the Canaries in Tenerife. The group has been awarded a total of 49 nights on the Carlos Sanchez Infrared Telescope from December 8 – 31, 1994 and again from April 7 – 20, 1995. The group expects to obtain complete infrared light curves of up to 15 short period Algols including β Per, TX UMa, RW Tau, δ Lib, and U CrB.

(h) Comparison with Hydrodynamical Models of Mass Transfer

Two-dimensional hydrodynamical simulations of mass transfer in short period Algol type binaries were performed using the numerical code VH-1 which was developed at the University of Virginia by the Numerical Astrophysics Group in which the P.I. participated (see Blondin 1993). This code uses the Piecewise Parabolic Method with a Lagrangian Remap (cf. Collella & Woodward 1984). The purpose of the simulations was to study the Hα emission from circumstellar gas in the Algols, as an extension of the hydrodynamical study of the gas flows in β Per by Blondin, Richards & Malinkowski (1995). Using observational evidence from the literature to constrain the gas stream properties, maps of the Hα emissivity in the two systems β Per ($P = 2.87^d$) and TT Hya ($P = 6.95^d$) were made in both Cartesian and velocity coordinates by the P.I.'s graduate student Mr. M. Ratliff. The velocity maps were then compared with Doppler tomograms constructed from observed Hα line emission in these systems. Since the tomograms cannot be directly transformed to spatial maps without additional information about the velocity field of the gas, the simulated Cartesian maps enabled the P.I. and Ratliff to interpret the dynamical processes which produce the features observed in the Doppler tomograms. The simulations produced asymmetric accretion structures with many features similar to those found in Doppler tomograms of such systems (Ratliff & Richards 1995, 1996). Moreover, the P.I. noted that the prominent emission source which covers the magnetically active secondary stars in the Doppler tomogram is absent in the hydrodynamical velocity maps; an indication that this extra source is not produced by mass transfer. The P.I. is confident that the extra source is from the chromosphere of the secondary (see Richards & Albright 1995).

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5. PERSONNEL SUPPORTED

The following personnel were supported by the research grant.

Number of Faculty, including PI: 1

Post Doctoral Staff: 0

Graduate Students: 3

Undergraduate Students: 3

Other: 0

(a) Undergraduate Supervision

R. D. Jones; Undergraduate Senior thesis research on "S-wave Doppler imaging of circumstellar material in β Persei," 1992.

L. Bowles; Summer research project on "SIMBAD and IUE search for short-period Algols; and the nature of chromospheric Hα line profiles," 1993.

M. Lugo; Summer research project on "Infrared facilities at U.S. Observatories; and Roche models of binaries," 1993.

L. Bowles: Summer undergraduate research project on "Doppler Imaging of Accretion Flows in Close Binaries," 1994

(b) Graduate Student Supervision

G. E. Albright; Ph.D. thesis research on "Magnetic Activity and Circumstellar Material in Algol-type Binaries," November 1992 – present (expected completion date: February 1996)

M. Swain; Summer research project on "Doppler Imaging of short-period Algols," 1993

M. Ratliff; M.A. thesis research on "Hydrodynamic Simulations of Hα Emission in Algol Binaries," September 1993 – 1995

(c) Graduate Theses

Ratliff, M. A. 1995, *Hydrodynamic Simulations of Hα Emission in Algol Binaries,* M.A. thesis, University of Virginia (December 1995)

6. PEER REVIEWED PUBLICATIONS (since 1992)

1. Richards, M. T. & Albright, G. E. 1993, "Evidence of magnetic activity in short-period Algol binaries," *Astrophys. J. Suppl.*, 88, 199 – 204
2. Albright, G. E., & Richards, M. T. 1993, "Circumstellar material in TX Ursae Majoris," *Astrophys. J.*, 414, 830 – 845
3. Richards, M. T., Albright, G. E. & Bowles, L. M. 1995a, "Doppler Tomography of the Gas Stream in Short-Period Algol Binaries," *Astrophys. J. Lett.*, 438, L103 – L106
4. Albright, G. E. & Richards, M. T. 1995, "The Transient Accretion Disk in the Algol-type Binary U Sagittae," *Astrophys. J.*, 441, 806 – 820
5. Blondin, J. M., Richards, M. T. & Malinkowski, M. 1995, "Hydrodynamic Simulations of the Mass Transfer in Algol," *Astrophys. J.*, 445, 939 – 946
6. Richards, M. T., Jones, R. D. & Swain, M. A. 1996, "Doppler Tomography and S-wave Analysis of Circumstellar Gas in Beta Persei," *Astrophys. J.*, 459 (March 1996) in press
7. Richards, M. T. & Albright, G. E. 1995 "Doppler Tomography of Chromospheres and Accretion Regions in Algol Binaries," in *Stellar Surface Structure*, ed. K. Strassmeier (Dordrecht: Kluwer), in press (8 pages)
8. Albright, G. E. & Richards, M.T. 1996, "Doppler Tomography of Accretion Disks in Algol Binaries," *Astrophys. J. Lett.*, in press
9. Richards, M. T., Waltman, E. B., Foster, R. S. & Ghigo, F. 1996, "Long-term continuous monitoring of 2GHz and 8GHz radio flares in β Per and HR1099," in preparation
10. Ratliff, M. A. & Richards, M. T. 1996, "Hydrodynamical Simulations of Hα Emission in Algol Binaries," in preparation
11. Richards, M. T., and Albright, G. E. 1996, "Magnetic Activity in Algol Binaries: Radio, Optical, Ultraviolet and X-Ray Observations" in preparation.

Book Chapters: none

7. INTERACTIONS

(a) Conference Presentations (since 1992):

1. Richards, M. T. 1992, "Magnetic activity in Algol-type binaries," in *Cool Stars, Stellar Systems and the Sun*, ed. M. Giampapa and J. Bookbinder, ASP Conf. Ser. Vol. 26 (San Francisco: ASP), 367 – 369
2. Albright, G. E., Richards, M. T. & Guinan, E. F. 1992, "Full-orbit Hα spectroscopy of short-period Algols," *Bull. Am. Astron. Soc.*, 24, 769
3. Jones, R. D., and Richards, M. T. 1992, "Doppler analysis of circumstellar emission in β Persei," *Bull. Am. Astron. Soc.*, 24, 768
4. Malinkowski, M., Etheridge, M, Blondin, J. M. & Richards, M. T. 1993, "Hydrodynamic Simulations of Mass Transfer in Algol," *Bull. Am. Astron. Soc.*, 25, 1424
5. Albright, G. E. & Richards, M. T. 1993, "Transient Accretion Disk in the Algol-type Binary U Sagittae," *Bull. Am. Astron. Soc.*, 25, 1424
6. Richards, M. T. & Albright, G. E. 1994a, "Full-Orbit Spectroscopy of Nine Short-Period Algols," in *Interacting Binary Stars*, ed. A. W. Shafter, ASP Conference Series (San Francisco: ASP), Vol 56, 393 – 396
7. Richards, M. T. & Albright, G. E. 1994b, "Facilities for Infrared Photometry and Spectroscopy of Short-Period Algols," in *Optical Astronomy From The Earth and Moon*, ed. D. M. Pyper and R. J. Angione, ASP Conference Series (San Francisco: ASP), Vol. 55, 251 – 254
8. Albright, G. E. & Richards, M. T. 1994a, "Evidence of Mass Transfer in TX UMa," in *Interacting Binary Stars*, ed. A. W. Shafter, ASP Conference Series (San Francisco: ASP), Vol. 56, 360 – 363
9. Albright, G. E. & Richards, M. T. 1994b, "Accretion Regions in Direct-Impact Algol Binaries," *Bull. Am. Astron. Soc.*, 26, 1414
10. Richards, M. T., Albright, G. E. & Bowles, L. M. 1994, "Doppler Tomography of Accretion Regions in Algol Binaries," *Bull. Am. Astron. Soc.*, 26, 1345
11. Albright, G. E. & Richards, M. T. 1995, "Circumstellar Material in Direct Impact Algol Systems," in *Circumstellar Matter*, eds. G. D. Watt and P. M. Williams (Dordrecht: Kluwer), 415 – 416 (reprinted in *Astrophys. Space Sci.*, 224, 415 – 416)
12. Richards, M. T., Albright, G. E. & Bowles, L. M. 1995b, "Doppler Tomography of Accretion Regions in Algols," in *Circumstellar Matter*, eds. G. D. Watt and P. M. Williams (Dordrecht: Kluwer), 547 – 548 (reprinted in *Astrophys. Space Sci.*, 224, 547 – 548)
13. Richards, M. T. & Albright, G. E. 1995 "Doppler Tomography of Chromospheres and Accretion Regions in Algol Binaries," in *Stellar Surface Structure*, ed. K. Strassmeier (Dordrecht: Kluwer), in press
14. Ratliff, M. A. & Richards, M. T. 1995, "Hydrodynamical Simulations of Hα Emission in Algol Binaries," *Bull. Am. Astron. Soc.*, in press

(b) Invited Lectures (since 1992):

1. *Algol-type eclipsing binaries,* Annual Meeting of Virginia Association of Astronomical Societies, Charlottesville, Virginia, May 1992.
2. *Algol- The Demon Star,* Sigma Xi Scientific Research Society Annual Banquet, Appalachian State University, Boone, North Carolina, April 1994.
3. *Magnetism versus Accretion in Algol-type Binaries,* Department of Physics and Astronomy, Appalachian State University, Boone, North Carolina, April 1994.
4. *Rediscovering Algol,* Eighth Annual Southern Star Astronomical Convention, Wild Acres Retreat, Little Switzerland, North Carolina, May 1994.
5. *Circumstellar Gas in Direct Impact Algols,* Astronomical Institute, Academy of Sciences of the Czech Republic, Prague, Czech Republic, September 1994.
6. *Accretion Regions in Short-Period Algols,* Institute for Astronomy, University of Vienna, Vienna, Austria, September 1994.
7. *Accretion Regions in Algol-type Binaries,* Physics Department, North Carolina State University, November 1994
8. *Observational Evidence of Mass Transfer in Interacting Binaries,* Department of Astronomy, University of Indiana, January 1995
9. *Algol Binaries: Mass Transfer Caught in the Act!,* Department of Physics, Indiana State University, January 1995
10. *Magnetic Activity and its influence on Accretion Processes in Algol-type Binaries,* Kiepenheuer-Institut fuer Sonnenphysik (Solar Physics Institute), Freiburg, Germany, June 28, 1995
11. *Image Reconstruction of Binary Stars Using Tomography,* Mathematisches Forschungs -institut (Mathematics Research Institute), Oberwolfach, Germany, July 5, 1995
12. *Doppler Tomography of Chromospheres and Accretion Regions in Algol Binaries,* IAU Symposium 176 on *Stellar Surface Structure*, Vienna, Austria, October 12, 1995

(c) Cooperative Activities with Other Laboratories

Since January 1995, the P.I. has been collaborating with research scientists Dr. E. Waltman and Dr. R. Foster at the Naval Research Laboratory (NRL) and Dr. F. Ghigo the National Radio Astronomy Observatory (NRAO). These scientists have expertise with the NRL radio interferometer at Green Bank Observatory, Green Bank, West Virginia, and have helped the P.I. collect observations of radio flares of three binary star systems: β Per, V711 Tau (HR 1099), and δ Lib. This collaboration has been successful in detecting several strong flares from two of the three objects (see Section 3(f)). The monitoring program is expected to continue through 1996, and the results will be used to interpret the evidence of the chromosphere found from the hydrogen spectra.

8. RELATED OBSERVING AWARDS

(a) **National Solar Observatory** (NSO), National Optical Astronomy Observatories, observing awards of 63 nights on the 1.5m McMath telescope to study *Full-orbit Hα spectroscopy of short-period Algol-type binaries,* 1990 – 1993.

(b) **Kitt Peak National Observatory** (KPNO) observing awards for work on the 0.9m Coudé Feed Spectrograph:
Balmer-line spectroscopy of Short-period Algols, 12 nights in April and May 1993 (with Albright);
Simultaneous Balmer-line and IUE spectroscopy of Short-period Algols, 7 nights in June 1994 (with Albright);
Simultaneous Balmer-line, IUE and Radio Continuum Observations of Algols, 7 nights in December 1994 (with Albright – P.I., and P. Koubský – Czech Republic).

(c) **Teide Observatory**, Astrophysical Institute of the Canaries (CAT) observing awards for work on the 1.5m Carlos Sanchez Telescope in Tenerife, Spain:
Starspot activity on Algol secondaries, 10 nights in February 1994 (with Albright);
Starspot activity in Algol Binaries, 49 nights in December 1994, April and May 1995 (with C. Lazaro and M. Jesus Arevallo; Tenerife, Spain).

(d) **National Radio Astronomy Observatory** (NRAO) observing awards of 7 nights on the 140 ft. telescope at Greenbank, West Virginia to study *Radio Survey of Flaring events on Algol Secondaries,* at 8.4 GHz (with Albright – P.I.) in June and December 1994.

(e) **European Space Agency** (ESA) observing awards for work on the International Untraviolet Explorer (IUE) satellite:
RI 023: *Dynamics and Physical Properties of Accretion Regions in Algols,* (with P. Koubský, Academy of Sciences, Czech Republic; E. Guinan, Villanova University, U.S.A.; and Albright) 3 nights in June 1994;
SI 022: *Ultraviolet Spectra of Non-eclipsing Algols,* (with P. Koubský, Academy of Sciences, Czech Republic), 20 hours in 1996

(f) **Naval Research Laboratory** (NRL), Office of Naval Research (ONR) long-term observing award to study *Radio Flaring Activity in β Persei and HR 1099* with the Green Bank Interferometer (with E. B. Waltman, R. S. Foster (NRL), F. Ghigo (NRAO)), starting January 1995.

9. HONORS: none

10. INVENTIONS: none

11. TABLES and FIGURES

Table 1: Summary of Spectroscopic Observations

Object	Dates	Observatory	Spectral Lines	No. spectra
RZ Cas	1993 Mar	NSO	CaII H&K	2
	1994 Dec	KPNO	Hα	28
TV Cas	1994 Dec	KPNO	Hα	10
TW Cas	1994 Dec	KPNO	Hα	23
U CrB	1993 Mar, Apr	NSO	Hα, Hβ	250
	1993 May	KPNO	Hα, Hβ	26
	1994 Jun, Dec	KPNO	Hα, Hβ	68
SW Cyg	1993 May	KPNO	Hα	8
	1994 Jun, Dec	KPNO	Hα	39
CX Dra	1994 Jun	KPNO	Hα, Hβ	55
	1994 Jun	ESA-IUE	UV - SWP, LWP	14
TW Dra	1993 Mar, Apr	NSO	Hα, Hβ	105
	1993 Apr, May	KPNO	Hα, Hβ	100
S Equ	1993 Apr, May	KPNO	Hα	72
RY Gem	1994 Dec	KPNO	Hα	1
TT Hya	1994 Jun, Dec	KPNO	Hα	23
δ Lib	1993 Apr, May	KPNO	Hα, Hβ	170
AU Mon	1994 Dec	KPNO	Hα	13
β Per	1989 Sep, Oct	NSO – synoptic	Hα	10
	1990 Oct	NSO – synoptic	Hα	25
	1992 Oct	NSO	Hα	201
	1993 Mar	NSO	CaII H&K	2
	1994 Dec	KPNO	Hα	45
U Sge	1993 Apr, May	KPNO	Hα, Hβ	141
	1994 Jun	KPNO	Hα, Hβ	69
	1994 Jun	KPNO	CaII H&K	2
	1994 Jun	ESA-IUE	UV - SWP, LWP	16
V505 Sgr	1993 May	KPNO	Hα, Hβ	84
RW Tau	1990 Dec	NSO – synoptic	Hα	2
	1994 Dec	KPNO	Hα	38
V711 Tau (HR 1099)	1994 Dec	KPNO	Hα	28
TX UMa	1991 Feb	NSO – synoptic	Hα	14
	1992 Mar	NSO – synoptic	Hα	91
	1993 Mar, Apr	NSO	Hα, Hβ	231
	1993 May	KPNO	Hα	19
	1994 Jun, Dec	KPNO	Hα	25
RS Vul	1993 Apr, May	KPNO	Hα, Hβ	102

Figure 2: Cartesian (spatial) map of β Per which shows the disk (dotted circle) and localized HII region (shaded circle) found by Richards (1992). The small circular markers are placed along the gas stream trajectory at distances of $0.1s$. The high density localized region is found at about $0.4s$ from the L_1 point. The orbital phases are shown around the binary and the center of mass of the binary is marked by the plus sign. (Taken from Richards, Jones & Swain 1996, *Astrophys. J.*, 459, in press.)

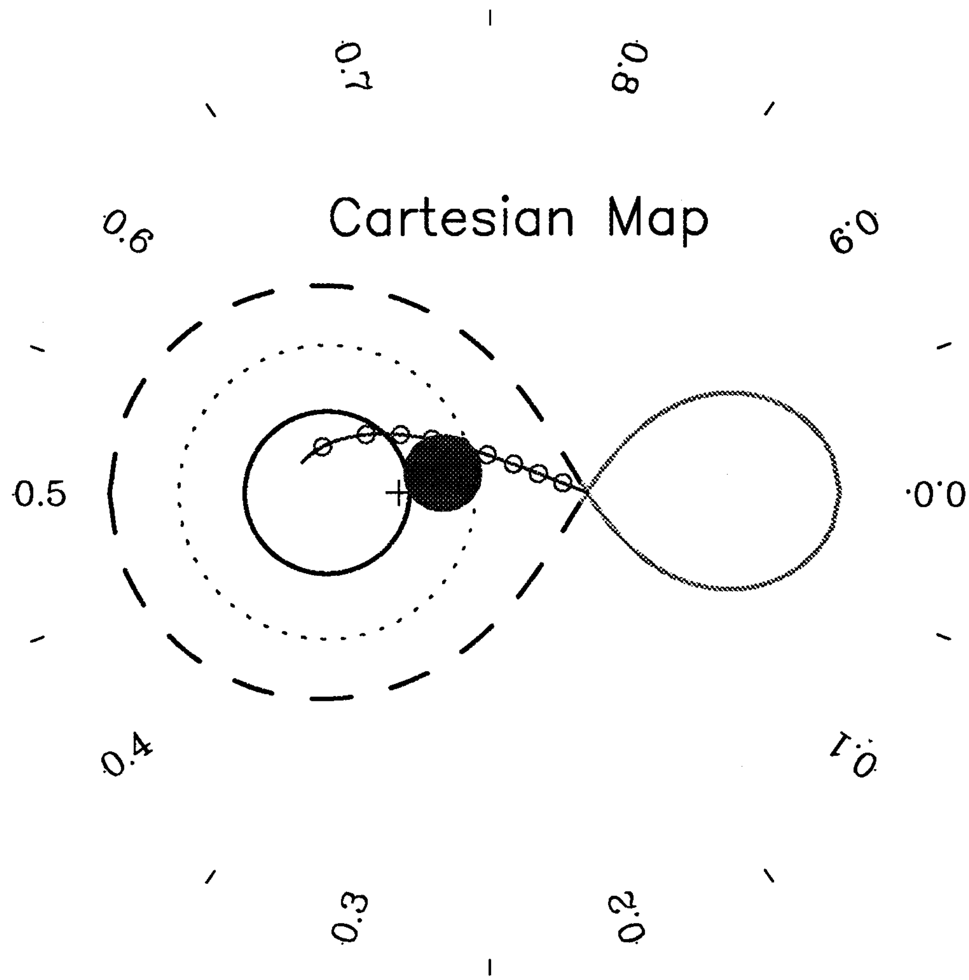
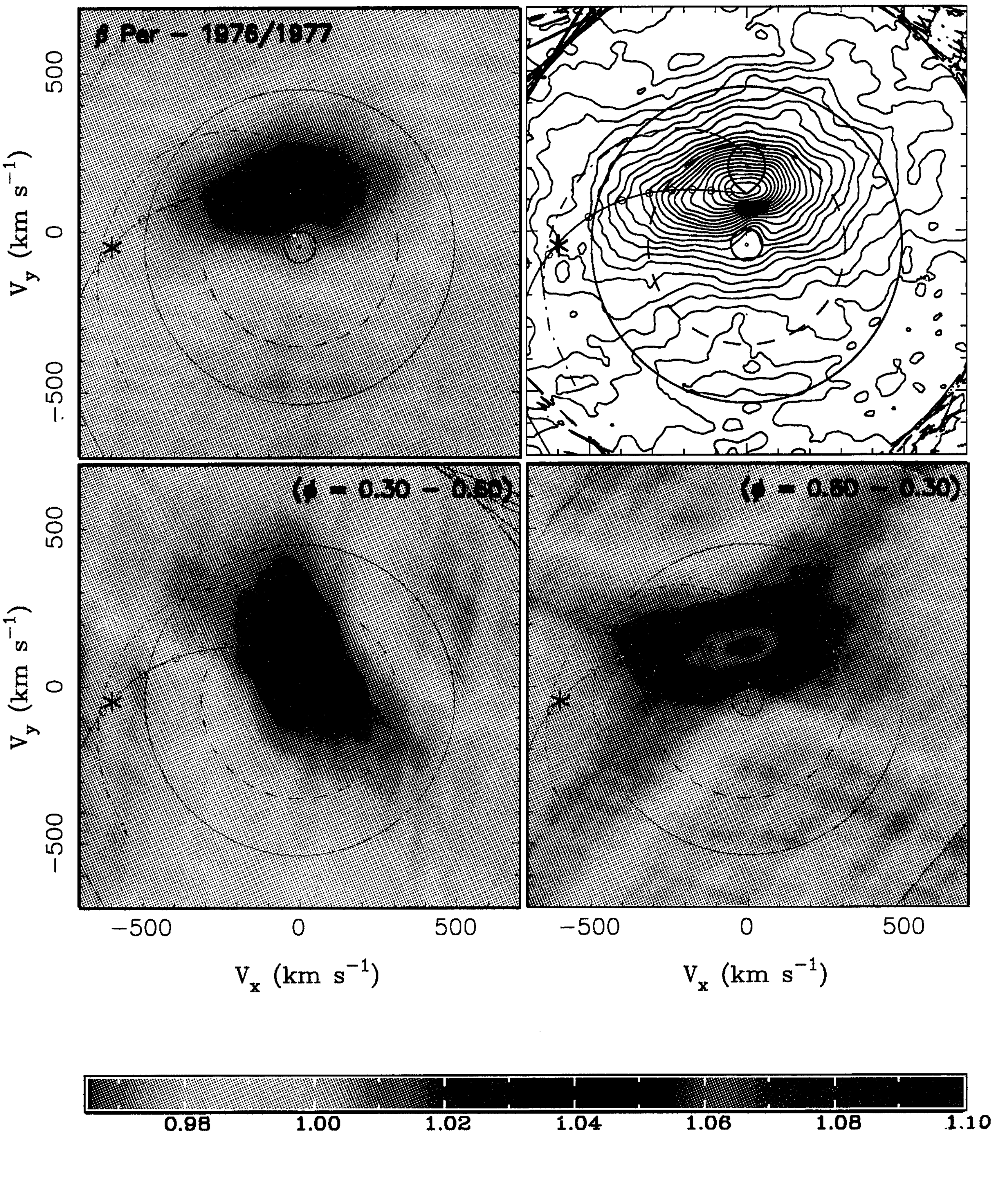

Cartesian Map
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Figure 3: Doppler tomograms of Algol (β Per). The composite color image (*upper left*) and contour image (*upper right*) display gas stream components that follow the free fall trajectory from the L_1 point in the rotating frame of the binary. The phase interval $\phi = 0.30 - 0.60$ (*lower left*) displays the enhanced localized region, accretion annulus arc and chromospheric emission from the secondary star. These are enhanced when the gas stream is occulted by the primary star. The phase interval $\phi = 0.60 - 0.30$ (*lower right*) displays the enhanced emission along the gas stream trajectory. The corresponding color wedge is shown at the bottom of the figure with intensity markers from 0.98 – 1.1 of the continuum flux, F_c. Here, the outlines of the Roche lobe of the secondary and the photosphere of the primary are given in velocity coordinates, assuming synchronous rotation. The outermost solid ring represents the location of a Keplerian disk at the surface of the primary, centered on the primary. The dashed inner ring represents the location of a Keplerian disk at the primary's Roche surface, also centered on the primary. The solid trajectory is the gravitational free fall path of the gas stream and is marked (small circles) at intervals of $0.1s$ from the L_1 point; while the dot-dashed trajectory is the Keplerian image of the gas stream. Finally, the asterisk marks the star-stream impact site. (Taken from Richards, Jones & Swain 1996, *Astrophys. J.*, 459, in press.)



β Per — 1976/1977
(φ = 0.30 – 0.80)
(φ = 0.80 – 0.30)
500
0
−500
V_y (km s^{-1})
V_x (km s^{-1})
0.98
1.00
1.02
1.04
1.06
1.08
1.10

Figure 4: Contour Doppler maps of magnetically active systems: β Per (1992), TX UMa (1993), RS Vul (1993), and V711 Tau (1994). (Taken from Richards & Albright 1995, in *Surface Stellar Structure*, ed. K. Strassmeier (Dordrecht: Kluwer), in press.)

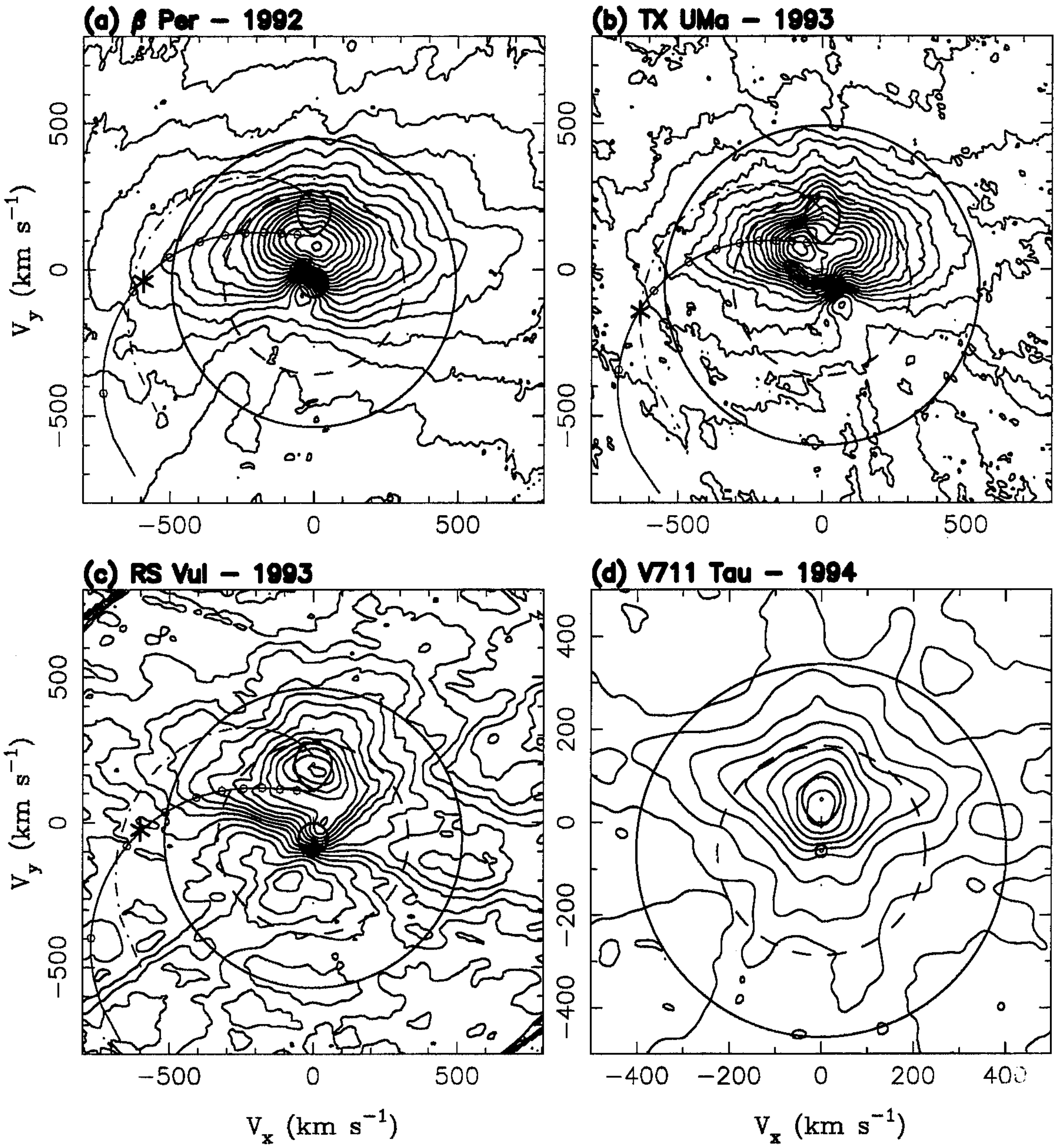

(a) β Per – 1992
(b) TX UMa – 1993
(c) RS Vul – 1993
(d) V711 Tau – 1994
V_y (km s^{-1})
V_x (km s^{-1})
−500
0
500
−400
−200
200
400

Figure 5: Color Doppler maps of the Algol binaries RW Tau (1994), β Per (1992), TX UMa (1993), U Sge (1993), U Sge (1994), U CrB (1993), U CrB (1994), S Equ (1993), RS Vul (1993), SW Cyg (1994), TT Hya (1994), and the RS CVn binary, V711 Tau (1994). The explanation for the maps is the same as for Fig. 3. (Taken from Albright & Richards 1996, *Astrophys. J. Lett.*, in press; and Richards 1996, in preparation.)